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FOR

MEDIA DELIVERY USING QUALITY OF SERVICE DIFFERENTIATION WITHIN A MEDIA STREAM

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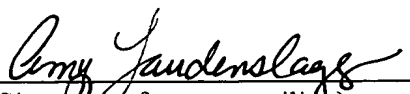*   *   *   *   *

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MEDIA DELIVERY USING QUALITY OF SERVICE DIFFERENTIATION WITHIN A MEDIA STREAM

BACKGROUND OF THE INVENTION

5   Field of the Invention

The present invention relates to communication equipment and, more specifically, to equipment for wireless local area networks (WLANs).

Description of the Related Art

10   IEEE Standard 802.11 has emerged as a prevailing technology for broadband access in WLAN systems and is regarded by many as a wireless version of Ethernet. The 802.11 legacy medium access control (MAC) is based upon best-effort service, which does not support quality of service (QoS) for users or applications. However, the increasing demand for streaming media (e.g., voice and video) transmissions, which typically have certain QoS requirements, prompted

15   the 802.11 Working Group to begin work on an extension to the standard. The upcoming 802.11e supplement standard will define enhancements to the legacy 802.11 MAC providing a QoS support facility.

Draft standard 802.11e (version D4.0 of November, 2002), the teachings of which are incorporated herein by reference, provides two mechanisms for the support of applications with

20   QoS requirements. The first mechanism, designated as Enhanced Distributed Coordination Function (EDCF), is based on differentiating priorities at which data traffic is to be delivered. The second mechanism allows for scheduling of transmission opportunities with the hybrid coordinator located at the access point (AP) of the WLAN. Various time-sharing schemes between the two mechanisms are also possible.

25   The EDCF is based on eight priority values, designated 0 to 7, which are analogous to IEEE 802.1d priority tags. Each data packet to be transmitted is provided with a priority value, based on which the packet is sorted into one of the following four access categories (ACs): best effort, video probe, video, and voice. Each AC contends for access to the wireless medium based on the corresponding QoS parameter set (PS) including, for example, the values of (i) CWmin and

30   CWmax specifying the contention window and (ii) arbitration inter-packet spacing. After winning a contention, an AC is allowed to transmit one or more packets in addition to the first packet without having to re-contend for access to the wireless medium for the transmission of the additional packets. Such transmission of multiple packets is referred to as data bursting.

Fig. 1 shows a block diagram of a representative WLAN system 100 having two prior-art

35   802.11e-compliant stations (STAs) 102 and 112 communicating over a wireless communication channel 122. For illustration purposes, STA 102 is a transmitting station and STA 112 is a

receiving station. Four data streams S0 – S3 corresponding to four access categories AC-n, where n = 0, 1, 2, 3, are applied to STA **102**. For each AC, STA **102** has a corresponding buffer **104-n** configured to queue data to be transmitted over channel **122** using a transmitter **108**. A controller **106** of STA **102** implements 802.11e MAC functions to govern application of data from buffers

5   **104-n** to transmitter **108**. More specifically, controller **106** is adapted to treat each AC-n as a separate EDCF contending entity having its own QoS parameter set (PS[n]) and maintaining its own back-off counter (BC[n]). When more than one AC-n of STA **102** finish their back-off procedures at the same time, controller **106** resolves any collision between those ACs using a virtual collision handler (VCH) in favor of the AC having the highest priority. For example, if the

10   collision occurs between the video and best-effort ACs, the video AC wins the contention and is given access to transmitter **108**. At STA **112**, a receiver **118** receives transmissions from STA **102** and a processor **116** processes the output of receiver **118** to generate four data streams S0′ – S3′ corresponding to data streams S0 – S3.

One problem with system **100** is that transmission of a given media stream, e.g., stream

15   S0, is relatively difficult to adapt to the fluctuating conditions of channel **122**. For example, a representative prior-art adaptation technique involves bit-rate adjustment at a source coder (not shown) that generates stream S0. This requires communication between the higher and lower network layers embodied by the source coder and processor **106**, respectively, which increases the overall complexity of the WLAN system and adds latency to its operation. In the absence of such

20   communication, STA **102** reacts to "bad-channel" conditions by dropping a certain number of data packets, which may result in unpredictable fluctuations of signal quality.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the present

25   invention, by a WLAN system adapted to apply QoS differentiation to a media stream to be transmitted from a transmitting station (STA) to a receiving STA of that system. The transmitting STA (or application) processes the media stream to generate a base sub-stream and one or more enhancement sub-streams for subsequent transmission over a wireless communication channel and assigns different priorities to different sub-streams. Depending on the channel conditions, the

30   transmitting STA may select to discard, without transmission, portions of data from enhancement sub-streams. The selection process is based on the assigned priority and operates to preserve as much of relatively high-priority data as possible. The receiving STA then processes the received data to generate a reconstructed media stream, which provides signal quality equal to or better than the signal quality supported by the base sub-stream. Advantageously, a WLAN system of the

35   invention is adapted to change signal quality dynamically and incrementally in a manner commensurate with current channel conditions without the need for communication between the

higher and lower network layers. In addition, it provides gradual and graceful degradation of signal quality when channel conditions deteriorate as opposed to abrupt degradation inherent in analogous prior art systems.

According to one embodiment, the present invention is a method of processing data
5   streams in a contention-based WLAN system, the method comprising: (A) generating two or more sub-streams corresponding to a first data stream; (B) assigning priority to each sub-stream, wherein at least two sub-streams have different priorities; and (C) transmitting data corresponding to each sub-stream based on the assigned priority.

According to another embodiment, the present invention is, at a transmitting station in a
10   contention-based WLAN system, apparatus adapted to process data streams, the apparatus comprising: (A) a device adapted to generate two or more sub-streams corresponding to a first data stream; and (B) a controller coupled to a transmitter, wherein: the transmitter is adapted to transmit data corresponding to the two or more sub-streams; and the controller is adapted to (i) assign priority to each sub-stream, wherein at least two sub-streams have different priorities and (ii) apply
15   sub-stream data to the transmitter based on the assigned priority.

According to yet another embodiment, the present invention is, at a receiving station in a contention-based WLAN system, apparatus adapted to generate an output data stream corresponding to a first data stream applied to a transmitting station in said system, the apparatus comprising: (A) a processor coupled to a receiver, the processor adapted to generate two or more
20   sub-streams corresponding to data received by the receiver from the transmitting station; and (B) a first device coupled to the processor and adapted to process the two or more sub-streams generated by the processor to generate the output data stream, wherein the transmitting station comprises: (i) a second device adapted to generate two or more sub-streams corresponding to the first data stream; and (ii) a controller coupled to a transmitter, wherein: the transmitter is adapted to transmit
25   data corresponding to the two or more sub-streams generated by the second device; and the controller is adapted to (i) assign priority to each sub-stream generated by the second device, wherein at least two of said sub-streams have different priorities and (ii) apply sub-stream data to the transmitter based on the assigned priority.

According to yet another embodiment, the present invention is a contention-based WLAN
30   system, comprising a transmitting station and a receiving station, wherein: the transmitting station is adapted to: generate two or more sub-streams corresponding to a first data stream; assign priority to each sub-stream, wherein at least two sub-streams have different priorities; and transmit data corresponding to the two or more sub-streams based on the assigned priority; and the receiving station is adapted to: generate two or more sub-streams corresponding to data received
35   from the transmitting station; and process said two or more generated sub-streams to generate an output data stream corresponding to the first data stream.

According to yet another embodiment, the present invention is, for a wireless network that supports priority-based transmission of data streams, a transmitting station capable of transmitting one or more data streams, wherein the transmitting station is capable of: for at least one data stream, generating two or more sub-streams corresponding to said data stream, each sub-stream having a different assigned priority level; and transmitting the two or more sub-streams based on the assigned priority levels, wherein, the transmitting station is adapted to selectively drop one or more sets of data in one or more sub-streams having relatively low priority levels when warranted by existing transmission characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

Fig. 1 shows a block diagram of a representative WLAN system having two prior-art 802.11e-compliant stations (STAs) communicating over a wireless communication channel;

Fig. 2 shows a block diagram of a WLAN system according to one embodiment of the present invention;

Fig. 3 shows a block diagram of a WLAN system according to another embodiment of the present invention; and

Fig. 4 shows a block diagram of a WLAN system according to yet another embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 2 shows a block diagram of a WLAN system 200 according to one embodiment of the present invention. System 200 has two 802.11e-compliant stations (STAs) 202 and 212 communicating over a wireless communication channel 222. For illustration purposes, STA 202 is a station adapted to process data stream S0 generated by an external coder (not shown) for transmission over channel 222, and STA 212 is a station adapted to receive over that channel transmissions from STA 202 and to generate data stream S0' corresponding to stream S0. In contrast to STA 102 of system 100 which assigns a single priority to each data stream, STA 202 of system 200 partitions stream S0 into two or more sub-streams and assigns different priorities to

different sub-streams to provide additional degrees of freedom when the system needs to dynamically adapt to the fluctuating conditions of channel **222**.

The following description illustrates operation principles of system **200** using an exemplary embodiment of the system adapted to process an MPEG-2 video stream S0, which is an

5   example of a broader class of hierarchical streams. One characteristic of a hierarchical stream is that it lends itself to relatively straightforward partitioning into sub-streams based on the stream's hierarchy. Such partitioning substantially involves (i) reorganizing the data already present in the stream and (ii) appropriately distributing the reorganized data between sub-streams. For example, relevant MPEG-2 hierarchy levels that may be used for such partitioning are: (1) sequence and

10   group of picture headers; (2) picture headers; (3) slice headers; (4) macro-block data (e.g., motion vectors); and (5) block data (e.g., discrete cosine transform (DCT) coefficients). More details on the MPEG-2 hierarchy can be found, for example, in International Standard ISO/IEC 13818-2, the teachings of which are incorporated herein by reference.

In system **200**, video stream S0 is applied to a partitioner **210** adapted to divide stream S0

15   into $k+1$ ($k \geq 1$) layers (sub-streams) L0 – Lk using partitioning based on division of DCT data . The principles of such partitioning are described, for example, in the ISO/IEC 13818-2 standard. Briefly, layer L0 is a base layer and each of layers L1 – Lk is an enhancement layer. Base layer L0 can be decoded independently, while each of enhancement layers L1 – Lk can only be decoded using the information contained in the corresponding lower layers. For example, enhancement

20   layer L2 is decoded using the information contained in layers L0 and L1. Progressive addition of information from a next enhancement layer to the information from the layers below that enhancement layer incrementally increases quality of the reconstructed video sequence. One skilled in the art will appreciate that other partitioning schemes can similarly be employed.

The ISO/IEC 13818-2 standard provides one partitioning mode and three primary

25   scalable-coding methods (i.e., data partitioning, signal-to-noise ratio (SNR) scalability, spatial scalability, and temporal scalability) and several hybrid methods, each of which combines two primary scalable-coding methods. Representative coders that can be used as partitioner **210** in STA **202** are disclosed in the ISO/IEC 13818-2 standard and in U.S. Patent Nos. 6,526,177 and 6,266,817, the teachings of both of which are incorporated herein by reference. One skilled in the

30   art will readily appreciate that other partitioning methods not described in the standard, e.g., into picture type differentiating I-, P-, and B-frames, can also be used.

For each layer (L0 – Lk), STA **202** has a corresponding buffer **204** configured to queue data to be transmitted over channel **222** using a transmitter **208**. Similar to controller **106** of STA **102**, a controller **206** of STA **202** controls application of data from buffers **204** to transmitter **208**

35   by assigning different priorities to different layers. Controller **206** then treats each layer as a separate EDCF contending entity (i.e., a virtual station) having the assigned QoS parameter set

(PS[i], i = 0, 1, ... k) and maintaining its own back-off counter (BC[i]). When more than one layer of STA **202** finish their back-off procedures at the same time, controller **206** resolves the collision using a VCH similar to the VCH of STA **102**.

In a preferred configuration, highest priority is assigned to base layer L0 and priority

5   decreases as the layer number increases. For example, in one configuration, controller **206** sets priority by assigning: (I) to layers L0 – L2, QoS parameter sets corresponding to the voice, video, and video probe ACs, respectively, of system **100** and (II) to all subsequent layers (if any), QoS parameter sets corresponding to the best effort AC of system **100**. In another configuration, controller **206** sets priority by assigning 802.11e priority values and custom-defined QoS

10   parameter sets to one or more layers, for example, by setting desired values for (i) CWmin and CWmax, (ii) arbitration inter-frame spacing (AIFS), and (iii) burst sizes.

Due to different priorities, data corresponding to different layers will on average spend different amounts of time in the corresponding buffers before an appropriate transmission opportunity is presented to the layer. For example, due to higher priority of base layer L0 with

15   respect to enhancement layer L1, the average retention time in buffer **204-0** of data corresponding to base layer L0 will be shorter than the average retention time in buffer **204-1** of data corresponding to enhancement layer L1. Similarly, the average retention time in buffer **204-1** of data corresponding to enhancement layer L1 will be shorter than the average retention time in buffer **204-k** of data corresponding to enhancement layer Lk, where k > 1. STA **202** uses this

20   retention-time differentiation to dynamically adjust its data transmission volume to correspond to the current conditions of channel **222**. More specifically, when a particular data packet is retained for a relatively long period of time due to relatively poor channel conditions, the packet is discarded without transmission. Since packets corresponding to relatively low-priority layers have relatively long retention times, a relatively large proportion of those packets will be discarded in

25   "bad channel" conditions.

To determine which data packets to discard, controller **206** maintains, for each data packet queued in buffers **204**, an individual timer having a threshold value. Preferably, different timers corresponding to the same buffer have identical threshold values, while timers corresponding to different buffers have different threshold values. In one configuration, a timer starts when the

30   corresponding packet is queued into the buffer. If the timer reaches its threshold value before the packet can be transmitted, then the packet is purged from the buffer without being applied to transmitter **208**. In another configuration, the timer for an enhancement packet starts when the base packet corresponding to that enhancement packet is transmitted. Consequently, the enhancement packet is discarded when the transmission delay for that packet with respect to the

35   base packet exceeds the corresponding threshold value.

At STA **212**, a receiver **218** receives transmissions from STA **202** and a processor **216** processes the output of receiver **218** to generate k+1 sub-streams L0′ – Lk′ corresponding to layers L0 – Lk. A reconstructor **220** then properly combines sub-streams L0′ – Lk′ to generate video stream S0′ corresponding to video stream S0. Reconstructor **220** is optionally adapted to use a

5 concealment technique as known in the art to mitigate loss of data corresponding to stream S0. Representative decoders that can be used as reconstructor **220** in STA **202** are disclosed in the above-cited U.S. Patent Nos. 6,526,177 and 6,266,817. In addition, the ISO/IEC 13818-2 standard itself provides a method of reconstruction including the step of discarding in a certain manner portions of layers L′k, k>1.

10 As already indicated above, to adapt to the fluctuating channel conditions, system **100** requires communication between higher and lower network layers embodied by a source coder and processor **106**, respectively, which communication adds complexity to the system. In the absence of such communication, STA **102** reacts to "bad-channel" conditions by dropping data packets, which results in lapses in the received video sequence and/or unpredictable and/or abrupt

15 degradation of video quality. In contrast, system **200** does not require communication between the higher and lower network layers and, yet, has the capacity for adaptively following channel conditions. More specifically, as already indicated above, system **200** reacts to "bad-channel" conditions by dropping portions of one or more enhancement sub-streams in the order of priority. For example, when the channel conditions begin to deteriorate, the sub-stream having the lowest

20 priority is dropped first, the sub-stream having the next lowest priority is dropped second, etc. As a result, video quality decreases gradually down to the quality level supported by the base sub-stream. No lapses in the received video sequence will occur as long as the base sub-stream is being received without interruption. As channel conditions improve, the dropped sub-streams are sequentially added back in to regain the original video quality. Thus, advantageously, system **200**

25 provides gradual and graceful degradation of quality as opposed to unpredictable and/or abrupt degradation typical to system **100**.

Fig. 3 shows a block diagram of a WLAN system **300** according to another embodiment of the present invention. System **300** is similar to system **200** and has two 802.11e-compliant stations **302** and **312** communicating over a wireless communication channel **322**. However, one

30 difference between systems **300** and **200** is that stream A0 applied to STA **302** is an embedded data stream that is divided into sub-streams by the source coder. One example of such data stream is an uncompressed audio stream, wherein the sub-streams are either LEFT and RIGHT channels or LEFT+RIGHT (SUM) and LEFT-RIGHT (DIFFERENCE) channels. Other examples of such data streams are compressed speech, audio, and/or video streams generated by an embedded coder.

35 Yet more examples of such data streams are streams generated by scalable video coders. In the art, the term "scalable" is often used interchangeably with the term "embedded", although

oftentimes the term "scalable" simply refers to the fact that the bit-rate is adjustable. One situation in which these terms are truly interchangeable is the situation of the "scalable modes" described in the ISO/IEC 13818-2 standard.

The following description explains operation principles of system **300** using, as an
5   example, a configuration adapted to process an audio stream. One skilled in the art will readily appreciate that a different embedded stream may similarly be processed.

Audio stream A0 is applied to an embedded encoder **310** of STA **302** adapted to generate k+1 (k ≥ 1) layers B0 – Bk using a selected embedded coding algorithm. Layers B0 – Bk are analogous to layers L0 – Lk of system **200** in that adding information from upper layers improves
10   audio signal quality corresponding to reconstructed stream A0′. Preferably, encoder **310** is implemented to attain the following characteristics: (1) parameterization of stream A0 and parameter allocation between base and enhancement layers is devised to provide acceptable signal quality with base layer B0 alone; (2) decoding of the base layer alone without enhancement layers is *a priori* accommodated by the design of the encoder and decoder; (3) enhancement layers can
15   only be decoded with the base layer and are produced with the assumption that the base layer will be available; and (4) addition of information from an enhancement layer to that from the preceding layers improves signal quality. When the base layer is lost, the decoder operates by using a concealment algorithm targeting the interval in time/space/location corresponding to the lost signal. Representative encoders that can be used as encoder **310** in STA **302** are disclosed in (1)
20   "High Quality Embedded Wideband Speech Coding Using an Inherently Layered Coding Paradigm" by Ramprashad, S.A.; Proceedings of the 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 2 Pages II1145 - II1148 and (2) "A Two Stage Hybrid Embedded Speech/Audio Coding Structure" by Ramprashad, S.A.; Proceedings of the 1998 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 1, Pages
25   337 –340, the teachings of which are incorporated herein by reference.

Subsequent processing of layers B0 – Bk in STA **302** is similar to the processing of layers L0 – Lk in STA **202** (Fig. 2). More specifically, for each layer (B0 – Bk), STA **302** has a corresponding buffer **304** configured to queue data to be transmitted over channel **322** using a transmitter **308**. A controller **306** controls application of data from buffers **304** to transmitter **308**
30   by assigning different priorities to different layers. Controller **306** then treats each layer as a separate EDCF contending entity having the assigned QoS parameter set and maintaining its own back-off counter, wherein collisions between layers are resolved using a VCH. Similar to controller **206**, controller **306** maintains an individual timer for each data packet queued in buffers **304**. A packet is discarded if its timer reaches a threshold value before the packet can be
35   transmitted.

At STA **312**, a receiver **318** receives transmissions from STA **302** and a processor **316** processes the output of receiver **318** to generate k+1 sub-streams B0′ – Bk′ corresponding to layers B0 – Bk. A decoder **320** then processes sub-streams B0′ – Bk′ by substantially applying a transform inverse to that applied in encoder **310** to generate audio stream A0′ corresponding to

5 audio stream A0. Representative decoders that can be used as decoder **330** in STA **312** are disclosed in the above-cited references (1) "High Quality Embedded Wideband Speech Coding Using an Inherently Layered Coding Paradigm" by Ramprashad, S.A.; Proceedings of the 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 2 Pages II1145 - II1148 and (2) "A Two Stage Hybrid Embedded Speech/Audio Coding Structure" by

10 Ramprashad, S.A.; Proceedings of the 1998 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 1, Pages 337 –340 and, also, in the ISO/IEC 13818-2 standard .

Similar to system **200** (Fig. 2), system **300** reacts to fluctuating channel conditions by dropping/adding one or more enhancement layers in some selected order and preferably in the order of priority. Thus, system **300** dynamically and incrementally changes signal quality in a

15 manner commensurate with the current channel conditions, which is advantageously different from abrupt signal quality fluctuations in system **100**.

Fig. 4 shows a block diagram of a WLAN system **400** according to yet another embodiment of the present invention. System **400** is similar to systems **200** and **300** and has two 802.11e-compliant stations **402** and **412** communicating over a wireless communication channel

20 **422**. However, one difference between system **400** and systems **200** and **300** is that system **400** is adapted to process multiple data streams compared to one stream in each of systems **200** and **300**. In system **400**, one or more data streams are processed to form layers, which are then transmitted using QoS priority differentiation, and the remaining streams are transmitted without QoS priority differentiation.

25 In the embodiment shown in Fig. 4, system **400** has four data streams S0 – S3, three of which (streams S0 – S2) are subjected to layering processing. For each of streams S0 – S2, system **400** has a corresponding layering device **410**. Depending on the stream type, the corresponding device **410** is either a partitioner similar to partitioner **210** (Fig. 2) or an embedded encoder similar to encoder **310** (Fig. 3). Outputs of devices **410** are connected to a distributor

30 switch **430**, which routes data packets corresponding to different layers to buffers **404** assigned to those layers, wherein a particular buffer **404-j** may receive packets corresponding to two or more different data streams. In addition, data stream S3 is applied directly to switch **430** and is routed to the buffer **404** to which that stream is assigned.

Subsequent processing in STA **402** of data packets stored in buffers **404** is similar to that

35 implemented, e.g., in STA **302** (Fig. 3). More specifically, a controller **406** controls application of data from buffers **404** to a transmitter **408**. At STA **412**, a receiver **418** receives transmissions

from STA **402** and a processor **416** processes the output of receiver **418** to generate packet streams corresponding to the packet streams applied to transmitter **408** by individual buffers **404-0 – 404-k**. A distributor switch **440** then de-multiplexes those packet streams into appropriate sub-streams corresponding to the layers generated by devices **410** of STA **402**. Each layer is then applied to a

5 corresponding decoding device **420**, which, depending on the stream type, is either a reconstructor similar to reconstructor **220** (Fig. 2) or a decoder similar to decoder **320** (Fig. 3). Each decoding device **420-m** applies processing inverse to that applied in layering device **410-m** to generate the corresponding reconstructed stream Sm', where m = 0, 1, 2. In addition, distributor switch **440** has a dedicated output corresponding to stream S3'.

10 While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

15 Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.

The present invention may be implemented as circuit-based processes, including possible

20 implementation on a single integrated circuit. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

The present invention can be embodied in the form of methods and apparatuses for

25 practicing those methods. The present invention can also be embodied in the form of program code embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, or any other machine-readable storage medium, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. The present invention can also be embodied in the form of program code, for example, whether

30 stored in a storage medium, loaded into and/or executed by a machine, or transmitted over some transmission medium or carrier, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic radiation, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. When implemented on a general-purpose processor, the program code segments combine with the

35 processor to provide a unique device that operates analogously to specific logic circuits.